2011-04-01

Embodied Emissions Abatement: a Policy Assessment using Stochastic Analysis

Adolf Acquaye
Technological University Dublin, adolf.acquaye@tudublin.ie

Aidan Duffy
Technological University Dublin, aidan.duffy@tudublin.ie

Biswajit Basu
Trinity College Dublin, basub@tcd.ie

Recommended Citation

Acquaye, A., Duffy, A., Basu, B.: (2011) Embodied emissions abatement-a policy assessment using stochastic analysis. Energy Policy, Volume 39, Issue 1, Pages 429-441, ISSN 0301-4215. doi:10.1016/j.enpol.2010.10.022

XML-IS

Our reference: JEPO 4562 P-authorquery-vx

AUTHOR QUERY FORM

ELSEVIER	Journal: JEPO Article Number: 4562	Please e-mail or fax your responses and any corrections to: E-mail: corrections.esil@elsevier.macipd.com Fax: +44 1392 285878

Dear Author,

Please check your proof carefully and mark all corrections at the appropriate place in the proof (e.g., by using on-screen annotation in the PDF file) or compile them in a separate list.

For correction or revision of any artwork, please consult http://www.elsevier.com/artworkinstructions.

Any queries or remarks that have arisen during the processing of your manuscript are listed below and highlighted by flags in the proof. Click on the Q link to go to the location in the proof.

Location in article	Query / Remark: click on the Q link to go Please insert your reply or correction at the corresponding line in the proof
Q1	Reference(s) given here were noted in the reference list but are missing from the text – please position each reference in the text or delete it from the list.
Q2	The reference given here is cited in the text but is missing from the reference list – please make the list complete or remove the reference from the text: Mongelli et al. (2005).
Q3	The reference given here is cited in the text but is missing from the reference list – please make the list complete or remove the reference from the text: Suh et al. (2002).
Q4	The reference given here is cited in the text but is missing from the reference list – please make the list complete or remove the reference from the text: Stromman et al. (2008).
Q5	The reference given here is cited in the text but is missing from the reference list – please make the list complete or remove the reference from the text: European Environment Agency(2008).
Q6	Please note that Table 5 was not cited in the text. Please check that the citation suggested by the copyeditor is in the appropriate place, and correct if necessary.
Q7	“Irish EPA (2010)” has been changed to “Irish EPA (2008)” as per the reference list. Please confirm.

Thank you for your assistance.

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Research highlights

Energy Policy ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Embodied emissions abatement—A policy assessment using stochastic analysis

Adolf Acquaye [a], Aidan Duffy [a,*], Biswajit Basu [b]

[a] *School of Civil and Building Services Engineering and Dublin Energy Lab, Dublin Institute of Technology, Bolton Street, Ireland*
[b] *Department of Civil, Structural and Environmental Engineering, Trinity College, Dublin 2, Ireland*

► The distribution of embodied GHGs is estimated for Irish apartment buildings. ► Monte Carlo analysis indicates this to be Wakeby distribution with a long tail. ► This tail can be targeted for improvement with appropriate policies. ► The effects of regulatory and informational emissions policies are investigated. ► These could result in a 27% reduction in GHGs and EU-27 carbon savings of €2bn.

0301-4215/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2010.10.022

Energy Policy ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Embodied emissions abatement—A policy assessment using stochastic analysis

Adolf Acquaye [a], Aidan Duffy [a,*], Biswajit Basu [b]

[a] School of Civil and Building Services Engineering and Dublin Energy Lab, Dublin Institute of Technology, Bolton Street, Ireland
[b] Department of Civil, Structural and Environmental Engineering, Trinity College, Dublin 2, Ireland

ARTICLE INFO

Article history:
Received 25 August 2010
Accepted 14 October 2010

Keywords:
Stochastic analysis
Embodied emissions policy
Construction sector

ABSTRACT

Policymakers traditionally focus on regulating operational energy use in buildings, ignoring other life cycle components such as embodied energy even though this may account for a significant portion of life cycle emissions. Data relating to embodied energy and emissions in buildings is limited. However, stochastic techniques can be used to estimate the distribution of such emissions from buildings. This helps policymakers identify which instruments are appropriate for achieving emissions reductions. A primary aim of this paper is to demonstrate this approach using a sample of apartment buildings in Ireland. A Monte-Carlo simulation suggests that the average probability distribution of embodied greenhouse gases in a sample of Irish apartment buildings is characteristic of a Wakeby distribution with a long tail which can be targeted for improvement through the implementation of appropriate policies. Two policies are investigated: one regulatory whereby the embodied emissions of building materials are limited to the 80th percentile of their current distributions; and one informational where buildings are given an embodied emissions rating. It is estimated that such policies could result in an average reduction of 450 gCO_2-eq/€ for the sample of apartment buildings analysed and could result in savings of €2bn to EU-27 countries in avoided carbon credits.

1. Introduction

Greenhouse gas (GHG) mitigation is now an important policy area for many countries due to an increasing global awareness of climate change, its impacts and the link between it and anthropogenic CO_2 emissions. Many GHG emissions policies have targeted the built environment since it is known to contribute significantly to national CO_2 emissions. For example, the United Nations Environmental Programme reported that in 1999 construction activities contributed to over 35% of total global CO_2 emissions – more than any other industrial activity – while buildings accounted for more than 40% of total energy consumption (UNEP, 2009). In the European Union, it is estimated that the building sector is responsible for 40% of total energy consumption, while some 50% of the UK's total CO_2 emissions are from buildings, with residential buildings alone accounting for approximately 27% (Dowden, 2008). However, these data measure operational emissions only – that is, emissions directly related to heating, cooling and powering a building – and ignore other important life-cycle components such as maintenance, demolition and, possibly most significantly, construction-related embodied energy and emissions.

Embodied energy is the total energy required to produce a product (such as a building) and can represent a significant fraction of its total life cycle energy requirements. For example, Chen et al. (2001) estimate that the CO_2 embodied in residential buildings can be as much as 40% of life cycle emissions. For unoccupied structures such as bridges, motorways and other infrastructure embodied energy accounts for over 90% of life cycle emissions (Maguire, 2009). The methodologies chosen to estimate both embodied and life cycle energy use will influence the result obtained (see inter alia Treloar et al., 2001; and Crawford, 2005): for example, certain approaches (such as process-based hybrid analysis) are more complete and give consistently higher values than alternative techniques. Despite the consequent difficulties in comparing results using different methodologies, Fig. 1 qualitatively illustrates the overall importance of embodied energy in the total life cycle for different buildings and infrastructure, as measured by the ratios of embodied energy to life cycle energy.

Despite the importance of embodied energy emissions, policies targeted at the building sector have focused historically on promoting operational energy efficiency, the deployment of renewable energy supply (RES) technologies and have failed to directly target embodied CO_2 equivalent (hereafter referred to as ECO_2-eq). Given the recognised importance of life cycle assessment in evidence-based policymaking (Kenny et al., 2010), this is a significant omission.

* Corresponding author. Tel.: +3531 4023940; fax: +3531 4023720.
E-mail address: aidan.duffy@dit.ie (A. Duffy).

0301-4215/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2010.10.022

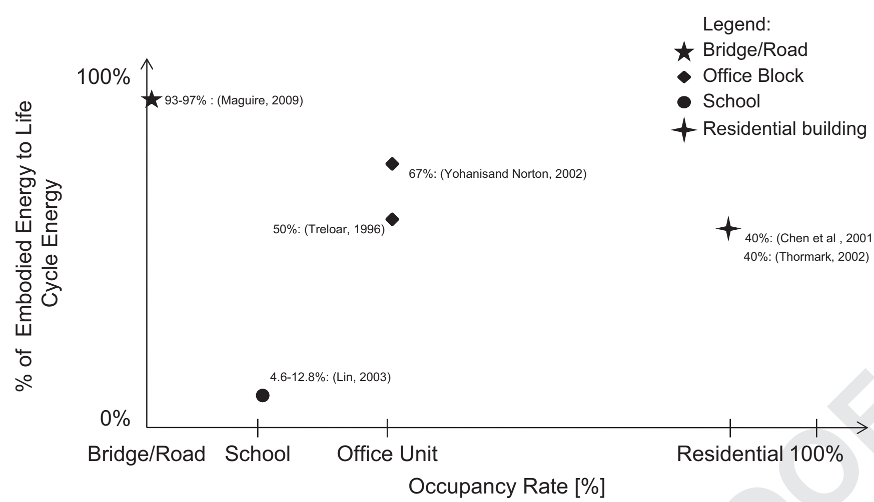

Fig. 1. Percentage ratio of embodied to life cycle energy in different infrastructure projects.

Evidence-based policymaking, however, requires quantitative information. This is problematic since embodied energy and emissions data are not specifically collected by national agencies. Therefore, the data used for estimating the embodied emissions and energies in buildings are typically from multiple sources, often of poor quality and frequently highly aggregated at an economic sectoral level. Existing deterministic approaches therefore yield highly averaged data which may not be very useful to policy-makers. In an attempt to overcome this problem, this paper applies a stochastic methodology to estimate the distribution of construction-sector emissions intensities for different structures so that policy options can be targeted effectively at appropriate parts of their distributions. Policies which can be used to reduce building-related GHG emissions are identified and methodologies for assessing embodied emissions are described. By way of example, the methodology is applied to a sample of apartment buildings in Ireland using input–output tables, process energy intensities, construction-sector survey data and bills of quantities. The impacts of relevant policies are tested to estimate their effects on embodied emissions' distributions.

In addition to its uses in framing GHG mitigation policies, an understanding of ECO_2-eq emissions in buildings enables building designers and contractors to play a role in environmental decision making and to reduce the emissions embedded in their designs as well as in their choice of building products and processes.

1.1. Embodied emissions distributions and policy

Best practice in estimating embodied emissions in buildings and other structures involves a hybrid approach, incorporating both process and input–output analysis (inter alia Crawford, 2005; Joshi, 2000; Lenzen and Treloar, 2002). These two approaches rely, respectively, on: process analysis-related data; and national sectoral economic data combined with environmental accounts to give emissions per unit of monetary output at basic prices. Process data are obtained at an industrial level by measuring fuel consumption and material flows during product manufacture or service delivery. Input–output energy analysis estimates the energy transfers between economic sectors based on transactions between these sectors. This can be extended to include environmental accounts containing data on sectoral GHG emissions to determine sectoral CO_2-eq emissions intensities. For process data, uncertainties arise due to variations in manufacturing processes and supply chains, measurement error and the use of out-of-date data. In the case of input–output data, a significant source of error is

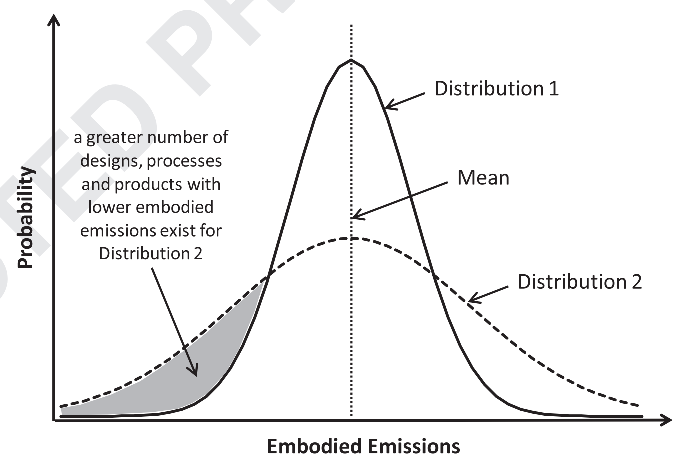

Fig. 2. Two possible normal ECO_2-eq probability distributions.

due to its highly aggregated nature: for example, a country's construction sector emissions intensity can be equally applied to house building and motorway construction.

It is normal practice to calculate embodied energy and emissions deterministically rather than probabilistically. Deterministic embodied energy values have been calculated for a variety of building types in different countries. Fay et al. (2000) have estimated the energy intensity of an Australian residential building to be 1803 GJ while Thormak (2002) calculated an embodied energy of 2.9 GJ/m^2 for a Swedish apartment. Treloar et al. (2001) has also estimated the embodied energy of a three storey office building to be 10.7 GJ/m^2. Due to the constraints mentioned above, these data may be representative of only a very small sample of buildings and may not provide sufficient information for decision makers to identify methods for reducing energy use in the construction supply chain. If however, the distributions of ECO_2-eq can be estimated, then decision makers could design targeted policies to reduce the overall fuel consumption and emissions from an economic sector or market segment.

An understanding of the distribution of embodied emissions for particular types of structures procured in different construction market segments is useful in the formulation of effective, targeted policies. For example, two hypothetical probability distributions of embodied emissions for a sample of buildings are shown in Fig. 2. Both have the same mean but different standard deviations: probability distribution 2 is more dispersed than distribution 1.

From a policymaker's perspective, there is likely to be more scope to regulate to reduce the mean emissions intensity in the case of 2 than of 1. Distribution 2 has a greater range of energy intensities than 1, indicating that a greater number of designs, processes and products are used in the buildings making up this sample. Therefore, greater scope may exist to deploy policies which force or encourage the construction of buildings with lower energy intensities.

Fig. 2 shows normal distributions of embodied emissions. However, if the distribution is skewed such as illustrated in Fig. 3, this could indicate that under current industry practices there is a minimum achievable emissions' intensity beyond which discontinuous technological learning is required to effect reductions; policymakers would need to be cognisant of this barrier. On the other hand, the long tail of high emissions for a minority of buildings might be targeted for improvement.

2. Methodology

The ECO_2-eq analysis undertaken in this study employs two methodologies: process and input–output analysis in a hybrid framework. Process based ECO_2-eq analysis typically utilises cradle-to-gate process flows to systematically compute known environmental inputs and outputs. The input–output approach, which is an extension of the theory originally developed by Leontief (1936), uses economic transactions between various sectors of the economy together with energy prices and carbon intensities to determine emissions intensities in the form of a mass of pollutant per unit of monetary value. Studies have shown how process and input–output analysis can be combined in a hybrid framework to Q2 derive the advantages of both methodologies (see also inter alia Q3 Mongelli et al., 2005; Suh et al., 2002; ~~Stromman et al., 2008~~). Process analysis can accurately measure direct energy input, but Q4 some energy inputs are not accounted for because of the truncation of the system boundary (Lenzen and Dey, 2000). Input–output analysis on the other hand has an extended system boundary but is less accurate mainly because of data aggregation (Born and Janiskee, 1996; Crawford, 2008).

Construction sector environmental emissions can be characterised as direct or indirect. The former are released as a result of activities directly related to construction on site (for example: excavation, fit-out and plant operation). The latter are associated with the use of energy in construction-related activities necessary for, but preceding site activities—these activities are 'upstream' of site work in the construction procurement supply chain (for example: energy used to manufacture building materials; excavation of raw aggregate; or design team activities).

Economic sectors and subdivisions thereof can be classified using the NACE classification system (NACE rev. 1). Construction (NACE 45) is subdivided into five sub-sectors (NACE 45.1–45.5) hereafter referred to as: Ground Works, Structural Works, Services, Finishes and Plant Operations. Construction activities in these sub-sectors consist of the following:

> Ground Works: Site preparation, demolition of buildings, earth moving, ground work, drilling and boring, etc. (NACE 45.1).
> Structural Work: Building of complete constructions or part thereof; civil and structural construction works, etc. (NACE 45.2).
> Services: Building installation, installation of electrical wiring and fittings, insulation, plumbing and other installations, etc. (NACE 45.3).
> Finishes: Building completion, joinery installation, plastering, floor and wall, covering, painting, glazing and general fit-out, etc. (NACE 45.4).
> Plant Operation: Construction plant and equipments, etc. (NACE 45.5).

In Ireland, direct energy expenditure by construction firms in each of these sub-sectors is recorded by the Central Statistics Office. Using these data together with average energy tariffs and Irish emission factors, direct emissions are estimated at the construction sub-sector level (Acquaye and Duffy, 2010).

Indirect input–output emissions intensities were estimated using data from the Irish national input–output (I–O) tables (Central Statistics Office, 2008a) that are compiled using data from national accounts as well as other national economic sources to show economic transactions between all product sectors of the national economy. The input coefficients of the economy-wide I–O tables are used to derive indirect I–O emissions intensities in the construction sector. This methodology is widely used and described in literature (see inter alia Bullard et al., 1978; Strømman and Solli, 2008; Treloar, 1997). In summary, the approach involves using Irish I–O tables (Central Statistics Office, 2008a), average energy tariffs (Sustainable Energy Ireland, 2009) and primary energy factors (Sustainable Energy Ireland, 2007) to determine total and direct I–O energy intensities per unit monetary value of construction sector output. The indirect I–O energy intensity is calculated as the difference between the total I–O and direct I–O energy intensities and is then converted to an indirect I–O emissions intensity using Irish emissions factors (Sustainable Energy Ireland, 2003). The direct requirement coefficient matrix of the Irish I–O table was used to evaluate the direct I–O energy intensity and the Leontief inverse matrix used to calculate the total domestic energy intensity (Miller and Blair, 1985; Treloar, 1997).

The direct requirement and Leontief inverse I–O coefficients for Ireland presented in the published national I–O tables are derived from domestic product flows only and omit energy inputs into imported products and services. Therefore, in order to account for the overall energy use of a product using I–O analysis, the energy inputs into imported goods and services used in the construction sector were included in the analysis by re-deriving the matrix of direct requirement coefficients and the Leontief inverse matrix. Firstly, the use table for imports was converted from a product-by-industry matrix into a product-by-product matrix using the product technology assumption (Eurostat, 2002) that assumes that each product is produced in its own specific way, irrespective of the industry where it is produced; secondary products are transferred from the industries where they are produced to those where they are the primary product. In this process, the columns are transformed from referring to industries to referring to products (Eurostat, 2002). The product technology model requires that for each product a primary producer is defined and the input structure of the primary producer becomes the starting point for deriving the input structure of the product. The transformation from product-by-industry to product-by-product can be explained by means of transformation matrices that are added to the original tables. The product-by-product presentation is a preferred

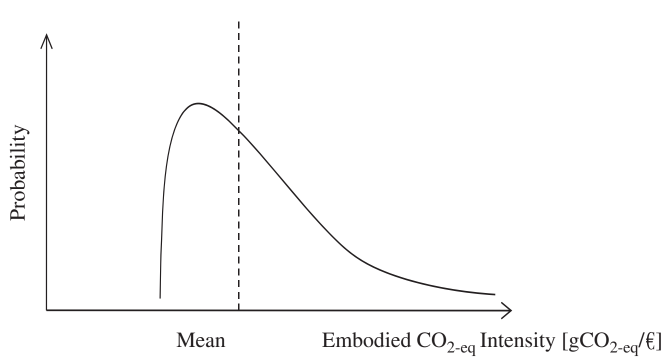

Fig. 3. A skewed ECO_2-eq probability distribution.

Please cite this article as: Acquaye, A., et al., Embodied emissions abatement—A policy assessment using stochastic analysis. Energy Policy (2010), doi:10.1016/j.enpol.2010.10.022

framework for I–O tables because they are more homogenous in their description of the transactions than industry-by-industry tables (Rueda-Cantucheab et al., 2009). In I–O analysis, a homogenous structure suggests that aggregated products in a sector have similar cost functions. I–O direct requirement coefficient matrix and the Leontief inverse matrix including imported energy inputs are then derived from the symmetric I–O table for domestic and imported product flows.

The addition of energy inputs into imported construction sector goods and services is important in an open economy such as Ireland's (SCCI, 2006) and provides greater information for decision making by designers and policymakers by considering total global impacts. Furthermore, given that approximately 56% of Irish imports are from the EU (Central Statistics Office, 2004) an understanding of all sources of emissions is important from an EU policy perspective.

In this paper, a stochastic hybrid ECO_2-eq analysis was carried out by deriving probabilistic input distributions for all the stochastic input variables for which sufficient data is available, namely:

- the process ECO_2-eq of all building materials; and
- the direct ECO_2-eq intensity of the disaggregated five sub-sectors of Irish construction.

The stochastic hybrid ECO_2-eq analysis was implemented using Monte Carlo simulation resulting in the generation of probabilistic ECO_2-eq intensity outputs. Data for apartment buildings in Ireland were used to illustrate the approach. Relevant policies were then identified and two were analysed based on the appropriateness of the stochastic embodied emissions model to assess them.

2.1. Embodied CO_2-eq (ECO_2-eq) intensity

Estimating ECO_2-eq intensity using a hybrid approach involves combining a variety of data:

- process data to determine the CO_2-eq embodied in the main building materials of the buildings;
- sub-sectoral direct CO_2-eq intensities to derive the direct CO_2-eq emitted on site during the construction of the buildings; and
- input–output analysis to estimate the indirect sectoral CO_2-eq emitted in the construction of the building.

Therefore, hybrid ECO_2-eq intensity can be expressed using the relationship

$$ECO_2\text{-eq} = \frac{[\sum_{x=1}^{n} M_x e_x] + [i_i \sum_{j=1}^{5} S_j + \sum_{j=1}^{5} i_{dj} S_j]}{\sum_{j=1}^{5} S_j + C_p} \qquad (1)$$

M_x is the mass of building material x [tonnes, t]; n the number of building materials for which process emissions intensities and quantities exist; e_x the process CO_2-eq intensity of building material x [gCO_2-eq/t]; i_i the input–output indirect CO_2-eq intensity of construction [gCO_2-eq/t]; j the number of construction sub-sectors; S_j the expenditure at basic prices classified by construction sub-sector, j on activities associated with the construction of the building [€]; C_p the cost of building materials analysed using process CO_2-eq intensity inventory [€]; i_{dj} the direct CO_2-eq intensity of each construction sub-sector j [gCO_2-eq/€].

Eq. (1) expresses the total hybrid embodied CO_2-eq intensity of the building as the sum of the process embodied CO_2-eq of the

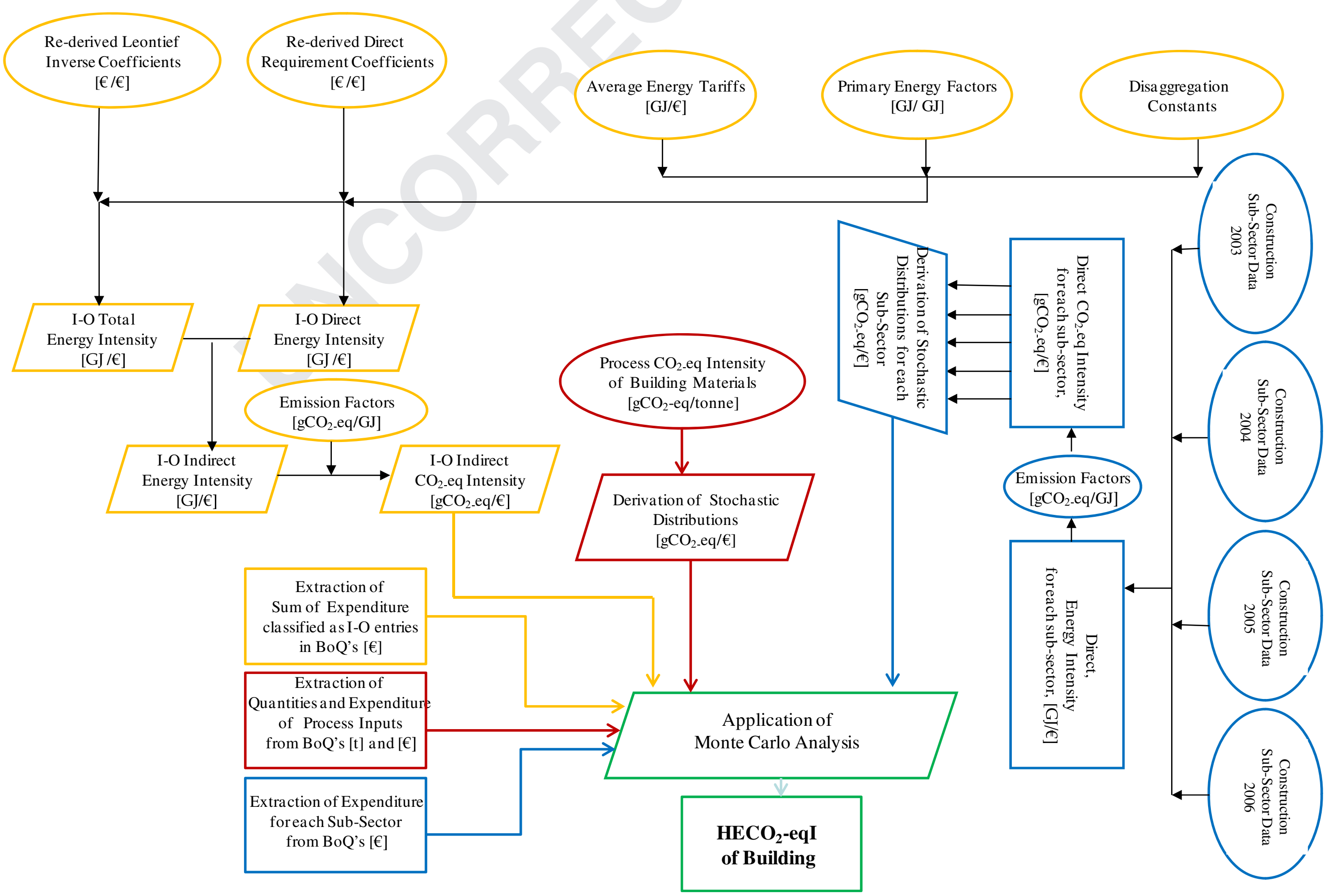

Fig. 4. Flow diagram of the methodology used to estimate the embodied CO_2-eq (ECO_2-eq) intensity.

Please cite this article as: Acquaye, A., et al., Embodied emissions abatement—A policy assessment using stochastic analysis. Energy Policy (2010), doi:10.1016/j.enpol.2010.10.022

building materials [gCO_2-eq], the I–O sectoral indirect embodied CO_2-eq of the building [gCO_2-eq] and the respective sub-sectoral direct embodied CO_2-eq [gCO_2-eq]. These embodied emissions are divided by the total cost of the building [$C_p + \sum_{j=1}^{5} S_j$] at basic prices [€] to give the total hybrid embodied CO_2-eq intensity of the building. Fig. 4 shows a flow diagram illustrating how various data are combined in the hybrid relationship.

To avoid double counting of inputs into the model for which process data has been collected, the following steps were taken:

- the price of building materials, C_p, to which process data were applied was subtracted from the bill of quantities, therefore the remaining expenditure in the bill of quantities is represented by $\sum_{j=1}^{5} S_j$;
- this sum is multiplied by the I–O construction sector indirect emissions to estimate total indirect emissions [$i_i \sum_{j=1}^{5} S_j$]; and
- individual sub-sectoral expenditures, S_j, are multiplied by the corresponding direct emissions coefficients, i_{dj} and then summed to estimate total indirect emissions [$\sum_{j=1}^{5} i_{dj} S_j$].

2.2. Stochastic analysis

2.2.1. Material process ECO_2-eq intensities

Cradle-to-gate process ECO_2-eq data for common buildings materials were obtained from the Inventory of Carbon and Energy database, ICE v1.6a (Sustainable Energy Research Group, 2008) and then fitted to probability density functions using EasyFit data analysis software. A total of 57 possible distributions were then ranked according to Kolmogorov Smirnov goodness of fit. Using the statistical parameters of the highest ranked fitted distribution, a set of 10,000 random ECO_2-eq intensities were generated for each of the building materials and used as input variables for the stochastic modelling. The process embodied CO_2-eq intensity distributions of concrete and steel – two of the most common building materials – are shown in Figs. 5 and 6 to illustrate the fitted distributions.

Table 1 shows some common building materials used in apartment buildings and the best ranked distribution which fits the process ECO_2-eq intensity for each. Table 1 also shows the parameters of the distributions used in the Monte Carlo simulation to generate the random ECO_2-eq intensities.

2.2.2. Direct sub-sectoral embodied CO_2-eq intensities, (i_{dj})

CO_2-eq emissions arise in each sub-sector as a result of energy used directly on the construction site and are calculated using disaggregated energy data collected for each construction sub-sector. Direct sub-sectoral embodied CO_2-eq intensities, (i_{dj}) are calculated for each sub-sector j using 2003, 2004, 2005 and 2006 construction company energy consumption data collected by the Irish Central Statistics Office in their Census of Building and Construction (Central Statistics Office, 2005, 2006, 2007, 2008b). The sample data from the construction firms was chosen to be representative of the Irish construction sector and methodological notes are available from the Irish Central Statistics Office (2008c). A total of 682 firms were sampled in 2003, 628 in 2004, 728 in 2005 and 1291 in 2006. The analysis of direct sub-sectoral embodied CO_2-eq intensities was undertaken from 2003 to 2006 in order to obtain a large sample size and smooth any variability in construction activities that might have occurred over the years. Table 2 shows a summary of the stochastic direct embodied CO_2-eq intensity distributions and the statistical parameters of the construction sub-sector which was averaged from 2003 to 2006. It is assumed that all fuel used was diesel since the vast majority of plant and construction machinery in Ireland operates on diesel fuel (Central Statistics Office, 2008b).

For each construction sub-sector, the equivalent primary energy in GJ used was calculated by multiplying energy expenditure [€] (Central Statistics Office, 2005, 2006, 2007, 2008b), average energy tariffs [GJ/€] derived from the energy balance for Ireland (Sustainable Energy Ireland, 2009) and primary energy factors [GJ/GJ] (Sustainable Energy Ireland, 2007). The energy intensity for each construction sub-sector is then derived in terms of the energy

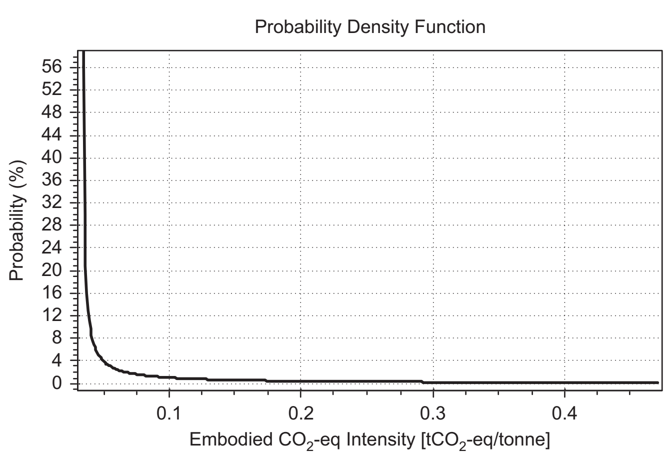

Fig. 5. Probability density distribution of concrete.

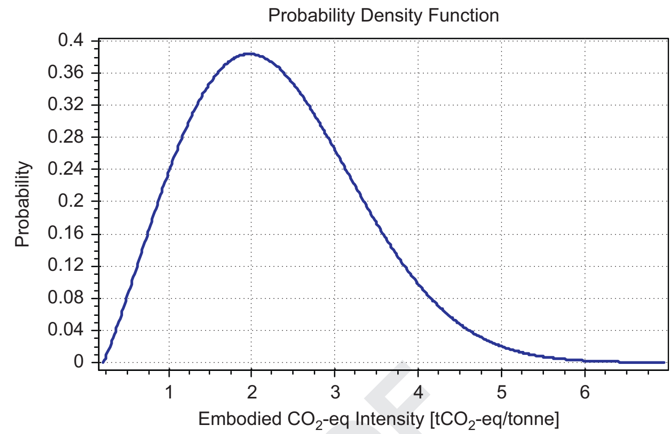

Fig. 6. Probability density distribution of steel.

Table 1
Main building materials, their ECO_2-eq distributions and statistical parameters.

Materials	Type of distribution	Distribution parameters
Concrete	Dagum function	$k=0.11$; $\alpha=0.4$; $\beta=0.95$; $\gamma=0.03$
Steel	Kumaraswany	$\alpha_1=2.1$; $\alpha_2=99.0$; $a=0.22$; $b=20$
Insulation	Burr function	$k=1.5$; $\alpha=1.8$; $\beta=1.7$; $\gamma=0$
Timber	Kumaraswany	$\alpha_1=0.34$; $\alpha_2=1.7$; $a=0.27$; $b=3.9$
Stone	Gamma	$\alpha_1=0.32$; $\beta=0.21$; $\gamma=0.06$
Brick	Kumaraswany	$\alpha_1=0.28$; $\alpha_2=1.7$; $a=0.18$; $b=2.8$

Table 2
Distributions and statistical parameters of the construction sub-sectors.

Materials	Type of distribution	Distribution parameter
Ground Work	Gen gamma (4P)	$k=1.2$; $\alpha=0.56$; $\beta=6.6$; $\gamma=0.02$
Structural Work	Log-logistic	$\alpha=1.1$; $\beta=0.02$; $\gamma=2.4\times10^{-6}$
Services	Frechet	$\alpha=1.0$; $\beta=0.02$; $\gamma=0$
Finishes	Dagum	$k=0.73$; $\alpha=1.6$; $\beta=0.39$; $\gamma=0$
Plant Operation	Frechet	$\alpha=1.1$; $\beta=11.0$; $\gamma=-2.9$

in GJ per Euro (€) output of each sub-sector. Irish emission factors [g/GJ] (Sustainable Energy Ireland, 2003) and global warming potentials (GWP) of the energy related emissions are then multiplied by the energy intensities to obtain the direct sub-sector CO_2-eq intensities i_{dj} [gCO_2-eq/€]. The GWP of the energy-related GHGs regulated under the Kyoto Protocol over a 100 year time-frame which are relevant to this study are: CO_2-1; N_2O-298 and CH_4-25. To normalise all data used to the 2005 baseline year in the analysis, the energy and construction price indices published by the Central Statistics Office (Central Statistics Office, 2009) are applied to the average energy tariffs and construction sub-sector output respectively. A baseline year of 2005 was adopted because it is the most recent year in which the national supply and use and input–output tables have been published for Ireland.

Direct sub-sector embodied CO_2-eq intensities of construction activities are treated as stochastic variables. The direct sub-sector CO_2-eq intensities for each of the firms under each sub-sector was fitted to probability density functions and ranked according to Kolmogorov Smirnov goodness of fit. The parameters of these distributions were used to generate input parameters for Monte Carlo simulation. Figs. 7 and 8 illustrate the direct embodied CO_2-eq intensity distributions of two of the five sub-sectors (sub-sector 2—Structural Works; and sub-sector 3—Services). The parameters of the distributions of all five sub-sectors are presented in Table 2 and the probability density functions in Table 3.

2.2.3. Case studies

Stochastic hybrid ECO_2-eq intensity distributions for a sample of seven apartment buildings in Dublin were estimated; a larger sample of detailed cost breakdowns was difficult to obtain for reasons of commercial sensitivity. The seven apartment case studies are described in the Table 4.

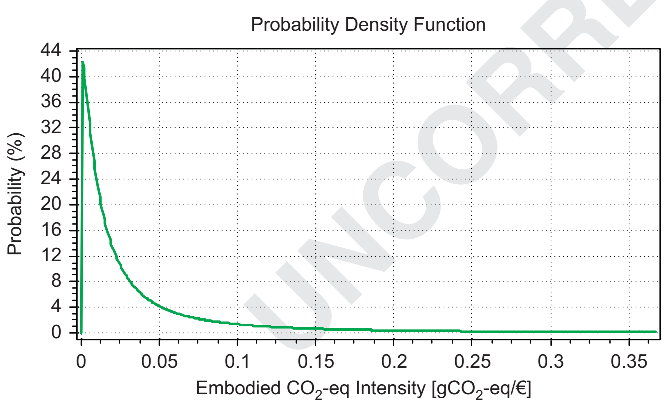

Fig. 7. Probability density functions of sub-sector 2—Structural Works.

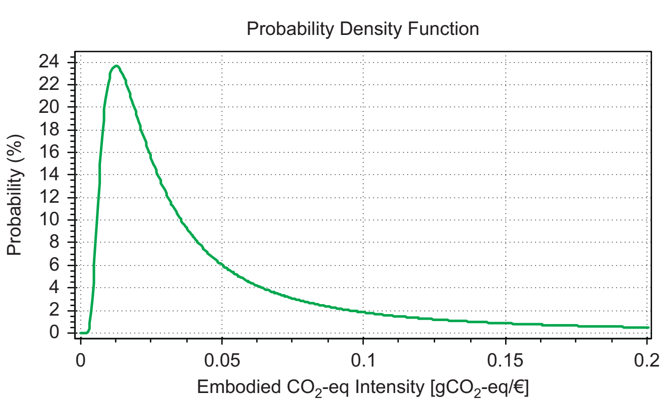

Fig. 8. Probability density functions of sub-sector 3—Services.

Table 3
Construction sub-sector distributions and the probability density functions.

Distribution	Probability density function
4-parameter generalized gamma	$f(x)=\frac{k(x-\gamma)^{k\alpha-1}}{\beta^{k\alpha}\Gamma(\alpha)}\exp\left(\left(\frac{\gamma-x}{\beta}\right)^{k}\right)$
Log-logistic	$f(x)=\frac{\alpha}{\beta}\left(\frac{x-\gamma}{\beta}\right)^{\alpha-1}\left(1+\left(\frac{x-\gamma}{\beta}\right)^{\alpha}\right)^{-2}$
Frechet	$f(x)=\frac{\alpha}{\beta}\left(\frac{\beta}{x-\gamma}\right)^{\alpha+1}\exp\left(-\left(\frac{\beta}{x-\gamma}\right)^{\alpha}\right)$
Dagum	$f(x)=\frac{ak((x-\gamma)/\beta)^{k\alpha-1}}{\beta((1+((x-\gamma)/\beta)^{\alpha})^{k+1}}$

The bill of quantities of each apartment building was analysed to identify total expenditure on building materials (C_p); and total expenditure in each construction sub-sector (S_j) was also collated. Direct I–O or indirect I–O ECO_2-eq data were then applied in the following manner:

- where material quantities were provided and process data were available for the materials, process analysis was preferentially applied;
- where costs for on-site activities were given and the necessary process data was unavailable, direct I–O analysis was used; and
- indirect construction I–O emissions intensities were applied in all other cases.

Monte Carlo simulation was used to generate ECO_2-eq distributions for each of the apartments using Eq. (1). Random input variables from the process ECO_2-eq intensity distributions and the sub-sector direct ECO_2-eq intensity distributions were used to calculate a stochastic ECO_2-eq distribution for each of the case studies. Deterministic values such as input–output sectoral indirect ECO_2-eq intensity and construction expenditure (obtained from the bill of quantities) were also calculated. Input–output sectoral indirect ECO_2-eq intensities were treated as deterministic since probability distributions for national input–output data are unavailable. These figures are compiled by aggregating data from a wide variety of sources including: the national balance of payments; industry sector surveys; private companies and industrial and commercial publications. Since the data are aggregated at a national level and are therefore representative of the overall population, and because no sampling errors were provided, there was no particular basis on which to infer ECO_2-eq distributions for input–output data. The results of 10,000 simulations were obtained for each of the seven apartment buildings and the relevant probability and cumulative ECO_2-eq distributions were derived. The 70,000 ECO_2-eq intensities for all seven apartment buildings were then combined and the probability and cumulative distributions derived to represent the ECO_2-eq intensity of 'average' apartment buildings in Ireland.

3. Results

3.1. Direct and indirect CO_2-eq intensities

The mean ECO_2-eq intensity of the Irish construction sector in 2005 was estimated to be 1364 gCO_2-eq/€. It can be seen in Fig. 9 that of this, almost 96% (1308 gCO_2-eq/€) was embodied indirect emissions. Total ECO_2-eq emissions in the Irish construction sector are therefore overwhelmingly dominated by indirect sources;

Please cite this article as: Acquaye, A., et al., Embodied emissions abatement—A policy assessment using stochastic analysis. Energy Policy (2010), doi:10.1016/j.enpol.2010.10.022

Table 4
General description of apartment buildings used in the case studies.

Apartments	Description of apartment buildings
Apartment 1	Concrete piled foundation, reinforced concrete frame with infill 215 mm block-work; 320 mm thick reinforced concrete slab with 400 mm × 600 mm reinforced concrete columns on 9 m × 9 m grids. External finishes included brickwork and render, double-glazed timber-framed windows, thermafloor insulation and concrete roof tiles. Internal finishes included timber stud partitions, plaster work and painting
Apartment 2	Reinforced concrete frame with minor structural steel to roof; 300 mm thick reinforced concrete slab with 400 mm × 400 mm reinforced concrete columns on 8 m × 8 m grids. Thermafloor insulation and external finishes include plaster work with gloss paint to wood work. Roof work consists of mastic asphalt roofing with rigid sheet covering and decking. Extensive mechanical installations made up of waste, water, gas, heating, HVAC and lift installations
Apartment 3	Reinforced concrete substructure, block work external walls 440 × 215 × 100, concrete work in concrete frame structure, wood work and precast pre-stressed concrete work for stairs, structural steel work fabricated members, internal walls partitioned with softwood and thermafloor insulation
Apartment 4	Reinforced concrete substructure with reinforced concrete in-situ concrete frame, fabricated members steel work, concrete work stairs 1.2 m wide, block work internal walls 100 × 215 × 440, in-situ concrete floors and slabs exceeding 150 mm reinforced and thermafloor insulation
Apartment 5	Structural steel work with fabricated members, brickwork and block work internal walls with concrete blocks 100 × 215 × 440. In-situ concrete floors slabs exceeding 150 mm thick and precast concrete 200 mm thick with span > 5.00 and < 7.00 m. Thermafloor insulation and structural steel work roof 254 × 146 × 37 kg/m Universal Beam
Apartment 6	Reinforced concrete substructure, brickwork and concrete work size 440 × 215 × 100, Floor insulation laid to underside of floor, in-situ concrete floor exceeding 150 mm thick. Concrete walls consist of reinforced in-situ concrete with thickness not exceeding 0.20 sqm. Concrete screed floor 75 mm thick with fabric reinforcement
Apartment 7	Reinforced concrete substructure, brickwork and concrete work size 440 × 215 × 100; Brick and block work external walls, coping to parapet 560 × 150. Precast concrete lintels, 100 × 65 mm, insulation board 100 mm thick, structural steel work 50 × 90 × 10 kg/m stainless steel. Carcassing roof with insulation

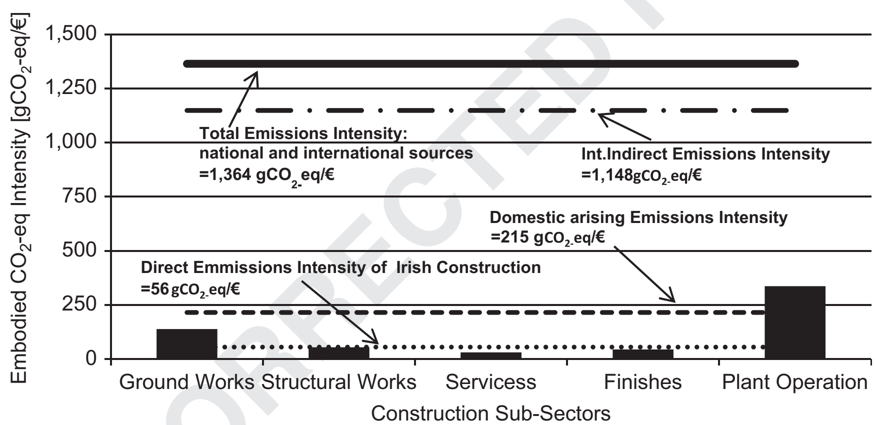

Fig. 9. National and international sources of direct and indirect emissions in the Irish construction sector.

direct ECO_2-eq emissions – which arise predominantly from energy use on the construction site – contributed only 56 gCO_2-eq/€. Fig. 9 also shows that the ECO_2-eq intensity of the Irish construction sector arising directly from energy transformations in the Republic of Ireland was estimated to be 215 gCO_2-eq/€, or 16% of total embodied emissions. This comprises 56 gCO_2-eq/€ (4% of total emissions) of direct embodied emissions and 159 gCO_2-eq/€ (12%) of indirect embodied emissions. The embodied emissions of Irish construction are therefore dominated by international sources estimated to be 1148 gCO_2-eq/€.

Fig. 9 also illustrates the results of the construction sub-sectoral analysis. The direct ECO_2-eq intensity of each of the five sub-sectors ranges from just over 31 gCO_2-eq/€ (Services) to 337 gCO_2-eq/€ (Plant Operations) with an output-weighted average of 56 gCO_2-eq/€. This latter value was dominated by sub-sector 2 (Structural Works) that had an ECO_2-eq intensity of 55 gCO_2-eq/€, due to the very high level of construction activity in that sub-sector relative to others. If it is assumed that the financial output of each sub-sector corresponds to the level of construction activity within that sub-sector, then sub-sector 2 (Structural Works) dominates accounting for approximately 79% of all construction activity, sub-sector 5 (Plant Operations) is the smallest with just 1%, while sub-sectors 1, 3 and 4 account for 2%, 15% and 3%, respectively. The high emissions intensities for the Ground Works and Plant Operation sub-sectors can be explained by the intensive use of construction machinery in these sectors (e.g. use of excavation machinery and haulage) and the associated greater fuel consumption.

3.2. ECO_2-eq intensity of apartment buildings in Ireland

Individual ECO_2-eq intensity distributions for each apartment building and the average ECO_2-eq intensity distribution representing the apartment building sector are shown in Figs. 10 and 11, respectively. For each of the apartment buildings, the differences between the deterministic value and the mean of the stochastic output over 10,000 simulations varied between 1.0% and 5.9%. All seven of the apartment buildings showed similar distribution characteristics with the exception of Apartment 2 which is more negatively skewed than the others. Apartment 2 has a skewness of 80.5 compared to between 3.04 and 3.59 for the other samples. The differences in this distribution can be attributed to two factors: first, Apartment 2 contained much greater quantities of mechanical and electrical services, the process probability density function for which resulted in negative skewing of the distribution for the overall building; secondly, indirect I–O data displaced a greater proportion of non-services-related process data, thus excluding more positively skewed distributions from the result ~~(Table 5)~~. Q6

The average ECO_2-eq intensity for all apartment buildings shown in Fig. 11 is characterised as a Wakeby distribution with

Please cite this article as: Acquaye, A., et al., Embodied emissions abatement—A policy assessment using stochastic analysis. Energy Policy (2010), doi:10.1016/j.enpol.2010.10.022

five parameters: shape parameters $\beta=1.4\times10^2$, $\gamma=1.3\times10^2$ and $\delta=0.77$ are shape parameters while $\zeta=0$ and $\alpha=1.5\times10^5$ location parameters. The quantile function describing the derived distribution for the sample of apartment buildings is

$$x(F)=1071[1-(1-F)^{1.4\times10^2}]-168[1-(1-F)^{-0.77}] \qquad (2)$$

The distribution had 100 class intervals with a bin or class size of 570 gCO_2-eq/€. The average distribution indicates that the mean ECO_2-eq intensity was found to be 1636 gCO_2-eq/€ while the median was 1127 gCO_2-eq/€. Assuming the sample to be representative of the population of Irish apartment buildings, then the 'average' Irish apartment building built in 2005 resulted in the emission of 1636 gCO_2-eq per Euro expenditure.

4. Policy options

4.1. National greenhouse gas mitigation policies

National emissions policies are driven by international agreements. For example, Kyoto imposes limits on the emissions of

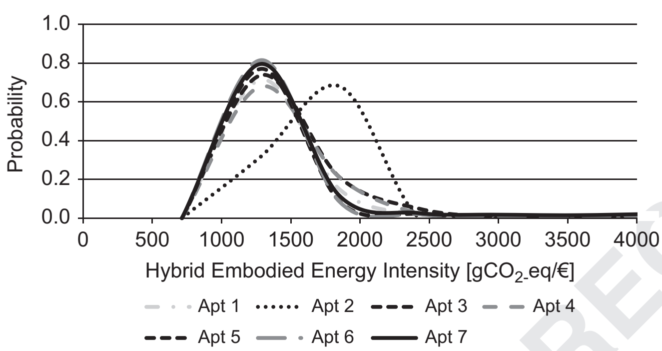

Fig. 10. Hybrid embodied CO_2-eq intensity distributions of the seven apartment buildings.

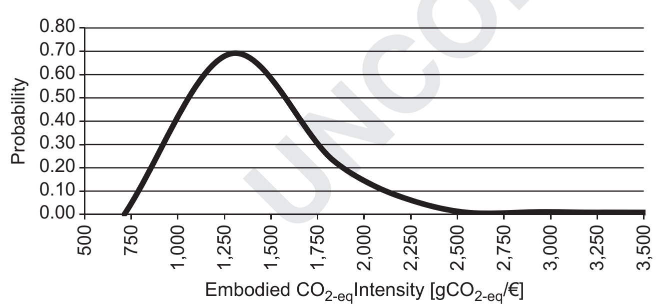

Fig. 11. Embodied CO_2-eq intensity probability distribution of apartment buildings in Ireland.

participating countries which must implement policies accordingly. The European Union's (EU) emissions and renewable targets – known as the '20–20–20 target' – sets limits on emissions and thresholds for renewables for member states including: a reduction of at least 20% in GHG emissions from all primary sources of energy by 2020 compared to 1990 levels and 20% of EU energy consumption to come from renewable energy sources by 2020. The long-term trend in international agreements is for increasingly challenging emissions targets. For example, although Copenhagen did not result in agreements on targets, it is still likely that any new agreement to succeed the Kyoto Protocol would aim to achieve greater emissions reductions—possibly a 30% cut by all developed nations by 2020 (Lutz and Meyer, 2009). The Fourth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC's AR4) also reported that to reduce global emissions by at least half of 1990 levels by 2050, developed countries collectively need to cut their emissions to 25–40% below 1990 levels by 2020 and by 80–95% by 2050 (European Commission, 2009). In line with these challenging targets, the EU has developed the European Strategic Energy Technology Plan aimed at developing RES technologies, low-energy buildings, energy conservation, a new generation of nuclear power plants and clean coal technologies and carbon capture and storage.

EU-27 member states' national policy options are framed within the overarching policies and targets agreed by the European Parliament and Council of the European Union. A number of policy measures have been introduced to help achieve the 20–20–20 target, most notably an enhancement of the EU's Emissions Trading Scheme, increasing the use of renewable energy, and a variety of energy efficiency measures. However, national governments have the freedom to choose which policies to pursue in order to meet national emissions reduction targets. In Ireland, for example, the National Climate Change Strategy 2007–2012 outlines a broad set of policies aimed at reducing national energy use and emissions up to 2012; the strategy also prepares for more stringent emission reduction requirements after this date. It outlines a variety of domestic measures to reduce national emissions supplemented by the purchase of carbon credits where necessary. Some of the national policies being considered by the Irish Government are outlined below (Irish Government, 2007, 2008, 2009):

- emissions' pricing (carbon taxation) and other market-based options such as road pricing;
- subsidisation of preferred technologies such as wind power (through feed-in tariffs) and electric cars (through capital grants to end-users);
- the regulation of products and services by setting direct or indirect limits on GHG emissions (for example, the introduction of car taxes based on direct CO_2 emissions and more stringent energy efficiency standards in houses); and

Table 5
Statistical parameters of the seven apartment building case studies

Apartments	*Central Tendency (Location)*				*Spread*			*Shape:* Skewness
	Det. value [gCO_2-eq/€]	Stochastic mean [gCO_2-eq/€]	% Difference	Median [gCO_2-eq/€]	Max [gCO_2-eq/€]	Min [gCO_{2-eq}/€]	Inter quartile range [gCO_2-eq/€]	
Apartment 1	2154	2133	0.98	1115	18,159	713	364	3.44
Apartment 2	1439	1354	5.90	1331	57,806	1325	133	80.5
Apartment 3	1319	1284	2.60	1214	2595	1061	127	3.04
Apartment 4	1605	1569	2.20	1236	7167	1075	131	3.59
Apartment 5	2311	2276	1.50	1237	18,101	1213	42	3.54
Apartment 6	1486	1455	2.10	1139	6481	1071	107	3.52
Apartment 7	1217	1162	4.50	1153	1372	1076	53	3.44

Please cite this article as: Acquaye, A., et al., Embodied emissions abatement—A policy assessment using stochastic analysis. Energy Policy (2010), doi:10.1016/j.enpol.2010.10.022

- the provision of information on energy consumption to consumers such as the Building Energy Rating scheme which provides a measure of the energy performance of commercial and domestic buildings.

These Irish policies are similar to policy measures adopted in other EU countries. For example, In Germany, the Renewable Energy Sources Act ensures priority access for renewable energy to the grid and guarantees a fixed priced tariff from renewable energy for 20 years (European Renewable Energy Council, 2009). Under the EU Directive 2002/91/EC, countries such as Denmark, UK, France, Netherlands and Luxembourg have also developed energy rating certification systems covering operational energy use by buildings (European Commission, 2002).

Currently, some energy and emissions policies exist that directly or indirectly affect embodied emissions. For example, eco-labelling influences consumer choice and thus directly affects the embodied emissions and the environmental impact of labelled products. Other instruments such as Emissions Trading Scheme (ETS) which targets large emitters such as the cement industry have indirect effects on construction sector embodied emissions by increasing prices and reducing demand, incentivising substitution and/or leading to the development of lower-emission production processes. Such policies affecting embodied emissions are discussed in more detail below.

4.2. Policies affecting embodied emissions

4.2.1. Information: eco-labelling

A number of voluntary measures for reducing embodied CO_2 and life cycle emissions using life cycle assessment (LCA) methodologies exist. The Eco-labelling initiative employs LCA and is widely deployed around the world. An 'Eco-label' is a label which identifies the overall environmental performance of a product or service within a specific product/service category based on life cycle considerations (Ball, 2002). Schenck (2006) recently reported that life cycle assessments undertaken in the manner outlined in ISO 14004 have formed the basis for many laws in Europe including: the 2002 Restriction on the use of Certain Hazardous Substances in Electrical and Electronic Equipment; 2003 Integrated Product Policy; 2004 EU Directive on Packaging & packaging waste and 2005 Waste Electrical and Electronic Equipment (WEEE). However, no such LCA or ECO_2-eq regulations exist specifically for the buildings sector even though ECO_2-eq in this sector can be a significant part of total product life cycle CO_2-eq emissions.

Voluntary eco-labelling schemes have however been specifically designed for the building and construction sector in a variety of countries. These include the US Green Building Council's Leadership in Energy and Environmental Design (LEED), the UK's BRE Environmental Assessment Method (BREEAM) and the Hong Kong Building Environmental Assessment Method (HKBEAM).

4.2.2. Emission trading scheme (ETS)

Among the energy and emissions policies instituted by the EU to control greenhouse gases are market-based instruments which generate economic incentives to invest in technologies with the lowest marginal emissions' abatement costs. The European Union's ETS was introduced to achieve average GHG emissions reductions of 8% below 1990 levels by 2012 for EU-15 member states (OpenEurope, 2007). The scheme, which works on a 'Cap and Trade' basis, is the largest multi-country, multi-sector GHG ETS world-wide where participants must buy and sell allowances. EU governments set emission caps for all installations such as energy and industrial plants covered by the scheme for the particular commitment period. The number of allowances allocated to each installation for any given period is determined on the basis of the National Allocation Plan. The ETS has an impact on emissions in the construction sector because it covers many large suppliers to the construction sector such as energy producers, cement manufacturers and the steel industry. For example, with the four cement factories in Ireland accounting for 5% of total national emissions in 2005 (Walker et al., 2009), 11% of the national allowance has been allocated to the cement sector (Irish EPA, 2008). In Germany, Q7 between 2005 and 2007, of the 495 million tCO_2 allocated per annum, 23.7 million tCO_2 (or 4.8%) was allocated to the cement industry and 33.7 million tCO_2 (or 6.8%) allocated to the Iron and Steel industry (DEHst, 2008). By attempting to incentivise CO_2-eq mitigation, the ETS aims to reduce the embodied emissions intensity in the building and construction sector by reducing indirect emissions from large polluters in the supply chain.

4.2.3. Carbon tax

Carbon tax is another form of market-based instrument. It is an indirect tax that sets a price for carbon dioxide emissions based on the Polluter Pays Principle. Carbon tax has been in place since the early 1990s in some EU member states including Sweden, Denmark, Netherland, Norway and the UK. In Ireland a carbon tax of €20 per tonne of carbon emitted was introduced in 2010. Critics of carbon tax have argued that its introduction in other jurisdictions has not generally resulted in a reduction in emissions (Bruvoll and Larsen, 2004). It is true that carbon taxation is particularly ineffective for goods or services with low elasticity's of demand; a good example is the transport sector where fuel price increases do not significantly reduce distance travelled, even by private cars (Litman, 2009). With regard to embodied emissions in structures and buildings, a carbon tax is unlikely to have a short-term impact on many direct emissions, for example those resulting from construction plant use, since there are few options for technology switching; however, eco-driving and behavioural change might reduce such emissions in the sector (Acquaye and Duffy, 2010). However, the associated reduction in overall building-related ECO_2-eq emissions would be small since it has already been shown that construction machinery has only a small impact on overall emissions in the Irish construction sector (see Fig. 10). The indirect impacts of a carbon tax on the construction supply chain could be more substantial, incentivising SMEs to adopt more energy efficient processes.

4.2.4. Subsidies

Subsidies provide incentives for favoured technologies or practices and can be classified as direct or indirect. Examples of direct subsidies include the biofuel GAYA project in France (EUROPA, 2010) as well as those for PV systems in Germany, Spain and Japan which have resulted in significant market growth in these countries (Sandén, 2003). In Ireland the Greener Home Scheme provides capital grants for energy efficient upgrades of existing dwellings and was established to encourage the introduction of energy saving insulation and control systems into older homes. The UK's Renewable Obligation and the Climate Change Levy (Renewable Energy Foundation, 2008) are examples of indirect subsidies: in the former a Renewable Obligation Certificate (ROC) is issued to electricity generators designed to incentivise renewable generation in the electricity generation market; the latter is a tax on delivered energy to non-domestic users which provides an incentive to increase energy efficiency and reduce CO_2 emissions. While direct subsidies are easier to monitor and quantify, indirect subsidies may have a more significant impact. However, although carefully designed subsidies can succeed in reducing greenhouse gas emissions if set in the right policy mix, they must be carefully designed since they are prone to lead to unintended or suboptimal outcomes (Legge and Scott, 2009). Therefore, unless the award of subsidies is based accurately on the marginal cost of carbon abated, they may prove to be an ineffective and expensive way to reduce emissions.

4.2.5. Regulation

Building designers and contractors are very familiar with direct regulation targeted at the building and construction sector. For example, in many developed countries building regulations which set minimum quality standards have a long history. Another example is the EU's Energy Performance of Buildings Directive (EPBD—2002/91/EC) which has recently been implemented at a national level through various legislative instruments in order to provide energy and emissions information to home owners and prospective purchasers for individual dwellings. This is similar to the Buildings' Sustainability Index (BASIX) certification in Australia and Japan's Energy Conservation Law, both of which provide information on the energy performance of buildings to purchasers and owners. Such information can then be used to improve the energy performance and efficiency of the building.

4.3. Policies targeted at limiting embodied emissions

Here, policies which can be targeted to reduce embodied emissions in buildings are identified and assessed. Market-based instruments such as the ETS and carbon taxation are not considered since their effects are broad and impact emissions from all economic sectors and many products and services. Targeted embodied emissions policies, however, may include: the provision of information; subsidies and regulation. For example, information on emissions intensities in the construction procurement supply chain is important for professionals when designing to minimise embodied emissions. The regulation of minimum energy efficiencies and operational emissions is common in the construction sector throughout the world; their extension to cover embodied emissions could therefore be culturally acceptable as well as easily integrated into the building procurement process. Subsidies are common in the building sector for promoting energy efficient and renewable energy supply measures, so their use to limit embodied emissions would build on accepted ways of doing business. However, the potential impact of subsidies is not considered further since the necessary data such as price elasticity of demand are not available.

Two policy options in the areas of regulation and information are therefore investigated using the stochastic models in order to estimate their impacts on the distribution of ECO_2-eq in the sample of apartment buildings. The impacts of the policies on input distributions are estimated and re-derived ECO_2-eq output distributions are used to assess their effectiveness.

4.3.1. Capping ECO_2-eq of building materials

This regulatory intervention would limit the ECO_2-eq intensities of all main building materials (i.e. those for which process data is available) to the 80th percentile of the stochastic distribution. The resulting changes in both the ECO_2-eq intensity output distribution and total CO_2-eq emissions savings are estimated. For example, Fig. 12 shows the truncated distribution of the steel where the embodied CO_2-eq intensity is limited to the 80th percentile of the stochastic distribution with no values higher than 2.99 tCO_2-eq/tonne. It is characteristic of Generalized Extreme Value Distribution and can be compared to the original distribution of steel in Fig. 6. The statistical properties of the truncated distribution for steel are presented in Table 6. The embodied CO_2-eq intensities of the other building materials are similarly capped.

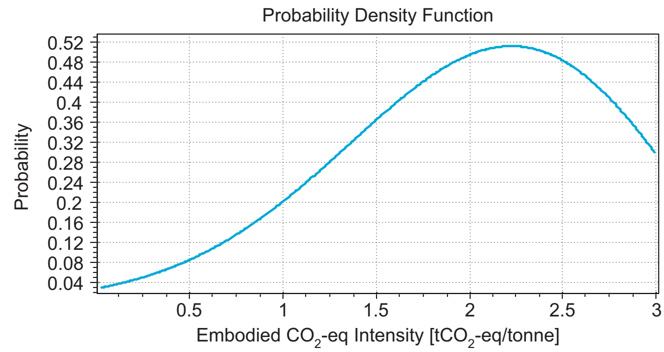

Fig. 12. Truncated distribution of steel: (Generalized Extreme Value Distribution).

Table 6
Statistical properties of truncated distribution of steel.

Units	Min	Max	Mean	Std. dev.	Class interval
tCO_2-eq/tonne	0.23	2.99	2.05	0.76	0.50

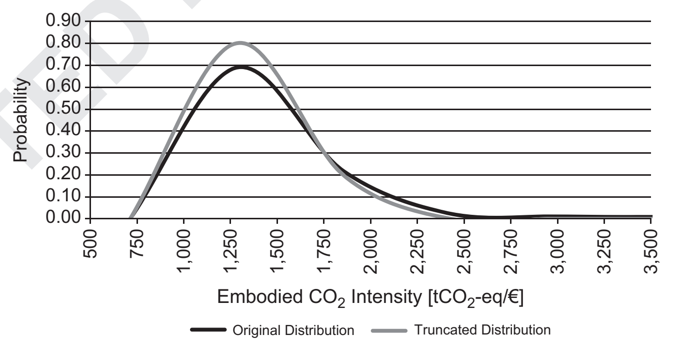

Fig. 13. Comparison between original and truncated stochastic embodied CO_2-eq intensities distributions.

The truncated distributions of all building materials are used to re-derive a new ECO_2-eq intensity for apartment buildings in Ireland together with other parameters using Eq. (1). Fig. 13 shows a comparison between the original average ECO_2-eq intensity output distribution for the sample of Irish apartment buildings constructed in 2005 (described above in Fig. 11) and the output distributions using the input distributions of common building materials truncated at the 80th percentile of their distributions. The resulting distribution shown in Fig. 13 is characteristic of a Cauchy distribution with a probability density function given by

$$f(x) = \left(53\pi\left(1+\left(\frac{x-1200}{53}\right)^2\right)\right)^{-1} \quad (3)$$

The new mean is 1186 gCO_2-eq/€ compared to 1636 gCO_2-eq/€ for the original distribution. The ECO_2-eq intensity distribution of apartment buildings in Ireland is therefore transformed from a Wakeby distribution into a Cauchy distribution and the average embodied CO_2-eq intensity is reduced by 450 gCO_2-eq/€ or 27%. Similarly, the new median is 1166 gCO_2-eq/€ compared to 1227 gCO_2-eq/€ for the original. It can also be seen in Fig. 13 that up to approximately 1700 gCO_2-eq/€ implementation of the policy will ensure that more buildings will have lower embodied emissions than if it were not; above this value the policy will result in a lower number of buildings at the tail end of the distribution which have higher emissions intensities.

Please cite this article as: Acquaye, A., et al., Embodied emissions abatement—A policy assessment using stochastic analysis. Energy Policy (2010), doi:10.1016/j.enpol.2010.10.022

By comparing the original ECO_2-eq intensity distribution to that derived using the truncated input distributions for common building materials, it is estimated that limiting the ECO_2-eq intensities of all buildings materials analysed to 80th percentile of the stochastic distribution results in an average saving of 450 gCO_2-eq/€ for the sample of apartments analysed. In 2005, the output of the Irish construction sector was estimated to be €32billion, of which residential construction accounted for approximately two-thirds of total output (Central Statistics Office, 2008d). Assuming that the average embodied emissions savings of 450 gCO_2-eq/€ could be applied to all residential construction in Ireland in that year, it is estimated that an embodied CO_2-eq saving of approximately 9.6 MtCO_2-eq could have been realised. A similar projection can be made at an EU-27 level to estimate the possible embodied CO_2-eq savings. In 2005, the EU-27 construction output was estimated at €1665 bn with new residential construction accounting for about 24.6% or €409.6 bn (Eurostat, 2010). Assuming that the average ECO_2-eq intensity saving of 450 gCO_2-eq/€ associated with above policy could have been applied to all residential development, it is estimated that 184 MtCO_2-eq of embodied CO_2-eq could have been saved. This represents 3.5% of total EU-27 emissions which were estimated at 5156.8 Mt in 2005 (~~European Environment Agency, 2008~~).

Assuming that the EU-27 would have had to pay for carbon credits equal to or exceeding this saving (that is, all emissions arise within the EU) and taking the cost of a carbon credit equal to that of the UN's Certified Emission Reductions credit rate of €11.10 per tonne (Bloomberg, 2009), it is estimated that the savings associated with the above policy would have been in the order of €2 bn. The costs of implementing such a policy would centre on the cost of information provision (e.g. measuring and communicating the emissions intensities of building materials) and auditing this information. Calculating these costs is beyond the scope of this paper, although it is worth commenting that much of the information (e.g. energy consumption, production output) and communication channels (product literature, technical support) is already collected and provided by manufacturers in the sector and the marginal cost of emissions-specific information is likely to be low—almost certainly significantly lower than €2 bn in savings.

4.3.2. *ECO_2-eq intensity rating scheme*

This policy would involve the provision of normalised embodied emissions information to building designers, developers, local governments, construction firms and other interested parties in order to allow them to rate the impact of a building relative to other similar buildings. Designers would calculate the embodied emissions associated with their building using supplier and other generic information. This could be compared to a cumulative ECO_2-eq intensity distribution for an appropriate building type such as that shown in Fig. 14 so that the relative emissions impact of the building could be assessed.

By showing building designers where their building lies within the ECO_2-eq intensity probability distribution of all buildings, they would be better placed to understand how their design compares to others and the potential for reducing embodied emissions through changes in design or construction practices. Fig. 14 is a cumulative probability distribution of the ECO_2-eq intensity of Irish apartment buildings which illustrates these relationships. The designer of Building 1, which has an ECO_2-eq intensity of 1284 gCO_2-eq/€, would know that its ECO_2-eq intensity is greater than 69% of similar buildings in that sector, while the designer of Building 2, which has an ECO_2-eq intensity of 3567 gCO_2-eq/€, would realise that only 5% of similar buildings have higher embodied emissions.

This informational policy could be extended to give a simple embodied emissions' rating (say A, B, C, D, E, F) to a dwelling – similar to that resulting from the Energy Performance of Buildings Directive – which is obtained from ECO_2-eq intensity distributions which are updated with data on new dwellings as they become available. Through the specification of the ECO_2-eq intensity of building materials on the market, the ECO_2-eq intensity of a building can be calculated and used to rate buildings based on ECO_2-eq intensity matrices such as gCO_2-eq/bedroom, gCO_2-eq/m^2 space or gCO_2-eq/€. An ECO_2-eq intensity rating can be achieved by classifying the combined ECO_2-eq intensity distribution on a scale from low ECO_2-eq to high ECO_2-eq, similar to the Certificazione Energetica Degli Edifici in Italy or the Building Energy Rating scheme employed in Ireland for operational energy use in buildings. For example, the distribution can be banded or classified as Band A to Band F; where Band A represents the lowest embodied CO_2-eq class and Band F the highest embodied CO_2-eq class. For the purposes of the Irish apartment buildings sector depicted in Fig. 15, classifications might be: Band A < 1000 gCO_2-eq/€; 1000 gCO_2-eq/€ < Band B < 1250 gCO_2-eq/€; 1250 gCO_2-eq/€ < Band C < 1500 gCO_2-eq/€; 1500 gCO_2-eq/€ < Band D < 1750 gCO_2-eq/€; 1750 gCO_2-eq/€ < Band E < 2000 gCO_2-eq/€ and B and F > 2000 gCO_2-eq/€.

An embodied energy and emissions rating scheme would complement the Building Energy Rating for operational energy use as part of the Energy Performance of Buildings EU Directive. Such an addition would provide a more holistic, life cycle understanding of the energy and emissions performance of buildings. From Fig. 15, it can be deduced that a minimum of 250 gCO_2-eq/€ emissions savings can be achieved, if through embodied CO_2-eq reduction techniques such as design choices, material selection, eco-driving, etc. the embodied CO_2-eq rating of the building reduces from Band D to Band B. The classification of a lower embodied CO_2-eq rating for a building would be the main incentive driving this scheme as it has been for similar schemes focussing on operational energy use. The United Nations Environmental Program, UNEP (2007) for example recently reported that mandatory certification and appliance labelling schemes are expected to save 81 MtCO_2 in Australia between 2005 and 2012. Support,

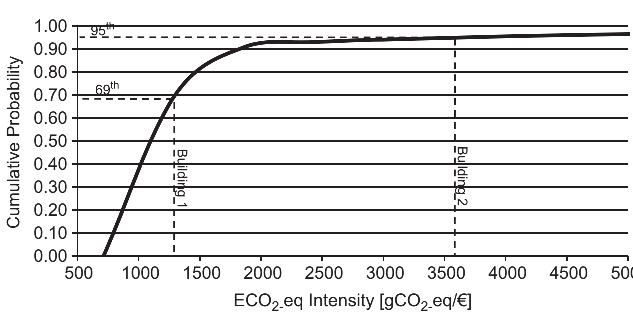

Fig. 14. ECO_2-eq intensity cumulative probability distribution of apartment buildings in Ireland.

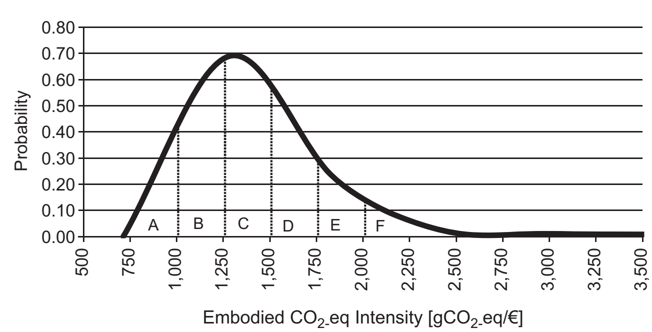

Fig. 15. Possible embodied CO_2-eq intensity rating scheme.

Please cite this article as: Acquaye, A., et al., Embodied emissions abatement—A policy assessment using stochastic analysis. Energy Policy (2010), doi:10.1016/j.enpol.2010.10.022

informational and voluntary labelling programs such as the US Energy Star program resulted in 13.2 $MtCO_2$ emissions savings in 2002 (UNEP, 2007) and was projected to result in a cumulative saving of 833 $MtCO_2$ by 2010 (Gillingham et al., 2006).

5. Conclusions

It is well known that energy use by buildings constitutes a significant proportion of total national energy use and consequently total national CO_2-eq emissions. However, emissions data used in policymaking tend to deal with operational energy use only and ignore other life cycle components such as construction and maintenance. These can account for a significant portion of life cycle emissions; for example, embodied emissions will account for a high proportion of life cycle emissions for structures which have low occupancy rates.

Data relating to embodied energy and emissions in buildings is limited. However, stochastic techniques can be used to estimate the distribution of emissions intensities in the building sector and sub-sectors. This is important for policymakers in helping them to identify what instruments are appropriate for achieving emissions reductions. A primary aim of this paper is to demonstrate this approach.

Based on process-based emissions data for common building materials, sectoral emissions data derived using input–output analysis and sub-sectoral construction firm census data, probability distributions of ECO_2-eq emissions intensities have been estimated for a sample of apartment buildings in Ireland. A Monte-Carlo simulation suggests that the mean ECO_2-eq probability distribution displays the characteristics of a Wakeby distribution with an average ECO_2-eq intensity of 1636 gCO_2-eq/€. Although a large proportion of the ECO_2-eq intensities for apartment buildings were at the lower end of the distribution, it had a long tail with 10% of buildings having an ECO_2-eq intensity greater than 1723 gCO_2-eq/€. This long tail can be targeted for improvement by policymakers by incentivising the selection of low ECO_2-eq intensity building materials, designs and construction techniques.

Market-based policies such as the ETS and carbon taxation already have an impact on embodied emissions. Two further targeted policies were investigated, one regulatory and one informational. The first would involve capping the ECO_2-eq of building materials at the 80th percentile of the stochastic distribution; the second would provide a normalised comparison of the ECO_2-eq intensity of buildings and/or an ECO_2-eq intensity rating scheme for buildings. Capping the ECO_2-eq intensity of building materials to the 80th percentile of their distributions results in an average saving of 450 gCO_2-eq/€ for the sample of apartment buildings analysed. Assuming that the sample is representative of emissions from residential developments in Ireland and the EU-27, then such a policy would have resulted in savings of approximately 9.6 and 184 $MtCO_2$-eq, respectively, if in force in 2005. Assuming that all avoided emissions originated in the EU-27 and assuming a carbon price of €11.10, then it would have had a value of €2 bn. It is difficult to estimate the impact of the informational policy, although it is anticipated that it would reduce the range of the distribution.

Further research on the feasibility and cost-benefit of the types of regulatory policies proposed here is necessary to furthering knowledge in this area. In the case of voluntary policies, assessments of the acceptability and likely uptake of measures by users would be beneficial. However, a key requirement to the development of effective policies to mitigate embodied emissions is the provision of better information: in many countries I–O data is too aggregated to analyse targeted interventions; and no process data is collected at a national- or EU-levels.

Uncited references

Q1

Lin, 2003; Treloar, 1996; Yohanis and Norton, 2002.

References

Acquaye, A., Duffy, A.P., 2010. Input–output analysis of Irish construction sector greenhouse gas emissions. Building and Environment 45, 784–791.

Ball, J., 2002. Can ISO 14000 and eco-labelling turn the construction industry green? Building and Environment 37 421–428.

Bloomberg, 2009. UN Certified Emission Reductions Credit Rate. Available at: 〈www.bloomberg.com〉.

Born, P., Janiskee, R.L., 1996. Input–output analysis: input of energy, CO_2, and work to produce goods. Journal of Policy Modelling 18, 217–221.

Bruvoll, A., Larsen, B.M., 2004. Greenhouse gas emissions in Norway. Do carbon taxes work? Energy Policy 32 493–505.

Central Statistics Office, 2004. Ireland and the EU, 1973–2003: Economic and Social Change. Stationary Office, Dublin, Ireland.

Central Statistics Office, 2005. 2003 Census of building and construction. ISSN: 1393-7103. Ref 153/2005, Ireland.

Central Statistics Office, 2006. 2004 Census of building and construction. ISSN: 1393-7103. Ref: 139/2006, Ireland.

Central Statistics Office, 2007. 2005 Census of building and construction. ISSN: 1393-7103. Ref: 134/2007, Ireland.

Central Statistics Office, 2008a. 2005 Supply and Use and Input–Output Tables for Ireland. Stationery Office, Dublin, Ireland, ISBN: 978-1-4064-2083-8.

Central Statistics Office, 2008b. 2006 Census of building and construction. ISSN: 1393-7103. Ref: 132/2008, Ireland.

Central Statistics Office, 2008c. Background Notes to Census of Building and Construction Methodology, Ireland. Available at: 〈http://www.cso.ie/surveysandmethodologies/surveys/census_of_building_and_construc_methodology.htm〉.

Central Statistics Office, 2008d. Construction and Housing in Ireland. Stationery Office, Dublin, Ireland, ISBN 1-4064-2074-6.

Central Statistics Office, 2009. Consumer Price Index, Principal Statistics, Prices, Ireland.

Chen, T.Y., Burnett, J., Chau, C.K., 2001. Analysis of embodied energy use in the residential building of Hong Kong. Energy 26, 323–340.

Crawford, R.H., 2005. Validation of the use of input–output data for embodied energy analysis of the Australian Construction industry. Journal of Construction Research 6, 71–90.

Crawford, R.H., 2008. Validation of a hybrid life-cycle inventory analysis method. Journal of Environmental Management 88, 496–506.

Deutsche Emissionshandelsstelle, DEHst, 2008. The German National Climate Protection Programme. Germany.

Dowden, M., 2008. Climate Change and Sustainable Development: Law, Policy and Practice, EG Books, 2008, ISBN: 978-0-7282-0523-9.

EUROPA, 2010. State aid: Commission clears French aid worth €18.9 million for the GAYA motor biofuels research programme, IP/10/349.

European Commission, 2002. Directive 2002/91/EC of the European Parliament and of the Council on the energy performance of buildings. Official Journal of the European Communities L001, 65–71.

European Commission, 2009. EU action against climate change. Leading global action to 2020 and beyond. 2009 edition.

European Renewable Energy Council, EREC., 2009. Renewable Energy Policy Review-Germany.

Eurostat, 2002. The ESA 95 Input–Output Manual – Compilation and Analysis – European Commission. Version 2002.

Eurostat, 2010. The EU-27 construction sector: from boom to gloom; Industry, trade and services; Statistics in focus; Issue number 7/2010.

Fay, R., Treloar, G., Iyer-Raniga., U., 2000. Life-cycle energy analysis of buildings: a case study. Building Research and Information 28, 32–41.

Gillingham, K., Newell, R., Palmer, K., 2006. Energy efficiency policies: a retrospective examination. Annual Review of Environmental Resources 31, 161–192.

Irish EPA, 2008. Ireland's National Allocation Plan for Emission Trading 2008–2012. Final Allocation Decision.

Irish Government, 2007. Delivering a sustainable energy future for Ireland. The Energy Policy Framework 2007–2020, pp. 1–68.

Irish Government, 2008. European Communities: Energy Performance of Buildings-Amendment Regulations. Statutory Instruments, S.I. No. 229 of 2008.

Irish Government, 2009. BioEnergy Action Plan for Ireland. Report of the Ministerial Task Force on BioEnergy.

Joshi, S., 2000. Product environmental life-cycle assessment using input–output techniques. Journal of Industrial Ecology 3, 95–120.

Kenny, R., Law, C., Pearce, J.M., 2010. Towards real energy economics: energy policy driven by life-cycle carbon emission. Energy Policy 38 (4), 1969–1978.

Legge, T., Scott, S., 2009. Policy options to reduce Ireland's greenhouse gas emissions. The Economic and Social Research Institute, Research Series 9, 1–56.

Lenzen, M., Dey, C., 2000. Truncation error in embodied energy analyses of basic iron and steel products. Energy 25, 577–585.

Lenzen, M., Treloar, G., 2002. Embodied energy in buildings: wood versus concrete; reply to BÖrjesson and Gustavsson. Energy Policy 30, 249–255.

Leontief, W., 1936. Quantitative input and output relations in the economic system of the United States. The Review of Economic Statistics 18, 105–125.

Lin, S.L., 2003. LCA-based energy evaluating with application to school buildings in Taiwan. Environmentally conscious design and inverse manufacturing. In: Proceedings of the Third International Symposium on EcoDesign, pp. 409–413.

Litman, T., 2009. Transportation Elasticities How Prices and Other Factors Affect Travel Behavior. Victoria Transport Policy Institute.

Lutz, C., Meyer, B., 2009. Environmental and economic effects of post-Kyoto carbon regimes: results of simulations with the global model GINFORS. Energy Policy 37, 1758–1766.

Maguire, A., 2009. Calculating the Carbon Footprint of Road Construction. 2009 National Local Government Asset Mgt & Public Works Engineering Conference, April 2009, pp. 1–20.

Miller, R.E., Blair, P.D., 1985. Input–Output Analysis: Foundations and Extensions. Prentice-Hall, Englewood Cliffs, NJ.

OpenEurope, 2007. Europe's dirty secret: why the EU Emissions Trading Scheme isn't working. UK.

Renewable Energy Foundation, 2008. UK Renewables Subsidies: A Simple Description and Commentary, London, UK..

Rueda-Cantucheab, J.M., Beutelc, J., Neuwahla, F., Mongellia, I., Loescheld, A., 2009. A symmetric input–output table for EU27: latest progress. Economic Systems Research 21, 59–79.

Sandén, B.A., 2003. The economic and institutional rationale of PV subsidies. Solar Energy 78, 137–146.

Schenck, R., 2006. A Practitioner Practitioner's Perspective s on LCA and Policy on a Global Basis. American Centre for Life Cycle Assessment, IERE, REACH Seminar.

Strømman, A.H., Solli, C., 2008. Applying Leontief's price model to estimate missing elements in hybrid life cycle inventories. Journal of Industrial Ecology 12, 26–33.

Sustainable Energy Ireland, 2003. Emissions Calculator-Version 5, Renewable Energy Information Office, Ireland. Available at: ⟨www.sei.ie/Publications/Statistics_Publications/Fuel_Cost_Comparison/Emissions_Calculator_Version5_01st_Oct_2003_.xls⟩.

Sustainable Energy Ireland, 2007. 1990–2006 Energy Statistics for Ireland. Energy Policy Statistical Support Unit. Cork, Ireland.

Sustainable Energy Ireland, 2009. Energy Balance by Energy Supply and Consumption, Year and Fuel Type. Energy Statistics Databank, Energy Policy Statistical Support Unit.

Sustainable Energy Research Group, 2008. Inventory of Carbon and Energy, Version 1.6a Beta. University of Bath, United Kingdom.

Swedish Chamber of Commerce Ireland, SCCI, 2006. Spotlight Sweden. SCCI News 7, pp. 1–10.

Thormak, C., 2002. A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential. Building and Environment 37, 429–435.

Treloar, G., 1997. Extracting embodied energy paths from input–output tables: towards an input–output-based hybrid energy analysis method. Economic Systems Research 9, 375–391.

Treloar, G.J., 1996. The Environmental Impact of Construction a Case Study. Australia and New Zealand Architectural Science Association (ANZAScA), Sydney, Australia, 1–95.

Treloar, G.J., Love, P.E.D., Holt, G.D., 2001. Using national input–output data for embodied energy analysis of individual residential buildings. Construction Management and Economics 19, 49–61.

United Nations Environmental Programme, UNEP., 2009. UNEP Governing Council Side Event: Energy and cities: Sustainable Building and Construction; 6 February, 2001—Nairobi, Kenya: Available at: ⟨http://www.unep.or.jp/ietc/focus/GC.asp⟩.

United Nations Environment Programme, UNEP., 2007. Assessment of Policy Instruments for Reducing Greenhouse Gas Emissions from Buildings. Report for the UNEP-Sustainable Buildings and Construction Initiative. Central European University.

Walker, N., Bazilian, M., Buckley, P., 2009. Possibilities of reducing CO_2 emissions from energy-intensive industries by the increased use of forest-derived fuels in Ireland. Biomass and Bioenergy 33, 1229–1238.

Yohanis, Y.G., Norton, B., 2002. Life-cycle operational and embodied energy for a generic single-storey office building in the UK. Energy 27, 77–92.

Please cite this article as: Acquaye, A., et al., Embodied emissions abatement—A policy assessment using stochastic analysis. Energy Policy (2010), doi:10.1016/j.enpol.2010.10.022